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to

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Applications of HCMM Satellite Data to the Study of Urban Heating Patterns

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Toby N. Carlson
Department of Meteorology
The Pennsylvania State University
University Park, PA 16802
(814-865-1606)

HCM-001

I. Introduction

Research into the application of HCMM measurements to the study of urban (and, in general, mesoscale) heating patterns is proceeding along two converging lines of approach. In the one approach, the satellite data will be processed to yield representative day-night patterns of temperature (for effective radiating black body surface) over 4 sites for essentially clear days. Ground albedos, a less important field, will have to be inferred, or at least estimated, from the visible radiance measurements. We have now reached the stage where we can produce smoothed Calcomp plots of the temperature fields from 130 x 130 matrices stored on BAT files. For HCMM, this will allow us to perform an analysis over an area approximately 65 x 65 km on a side, unless spot overlap occurs, in which case the area of analysis will be smaller. Present capabilities have also reached the point where we can begin to display color images of these files on the RAMTEK system belonging to the Penn State Remote Sensing Group.

The second facet of our research is in developing a reliable but computationally simple one-dimensional heat flux/surface temperature model which will allow us to determine the values of the effective substrate parameters necessary to yield the observed surface temperature response. HCMM will furnish us with two temperature observations per day, sufficient to estimate by graphical or numerical inversion of the model, the two most important substrate parameters in the model - thermal inertia and moisture availability. Ultimately we hope to be able to present maps of these parameters by inversion of the model and to infer the ground heat flux and surface energy budget over the area from the temperature fields. At present the nocturnal component of the model is being reformulated and the model itself tested against nighttime observations from various field experiments.

II. Anticipated Progress

Late in April, 1978, HCMM was launched into an orbit that will permit day-night pairs of satellite measurements to be made over the area of interest at three of the four sites to be studied - Washington, D.C., St. Louis, Mo., and Los Angeles. Houston, Texas will have coverage only at 36 hour intervals. Initial photographs and test material will be arriving shortly. Our aim continues to be the study of urban temperature patterns, in particular the ground temperature and, by inference, the surface/substrate parameters and the ground albedo by means of model inversion methods. It still remains our goal to be able to deduce the surface energy budget and to derive the model parameters necessary to predict the ground heating in prognostic numerical meso-scale models of the atmosphere. In conclusion, therefore, our current and future objectives remain identical to those stated in Part IIA of our first Quarterly Report of March 1, 1978. Further scientific discussion concerning these objectives and the techniques used to achieve them are contained in Appendix I, consisting of a symposium reprint, "Indirect Sensing of the Urban Heat Island by Satellite and the Measurement of Substrate Parameters Responsible for its Formation".

We are especially hopeful in being able to compare aircraft measurements of black body ground temperature (determined by NASA aircraft flying over St. Louis and over Washington, D.C. this summer) and black body ground temperature and surface albdeo (determined from the Penn State Aerocommander aircraft flying over St. Louis during the Regional Air Pollution Study (RAPS) of METROMEX during summers of 1974-6) with those obtained for those cities from the HCMM measurements. Although the comparisons will not be concurrent, there is a considerable persistence and stability of the surface characteristics over urban areas, the essentially features of the associated ground temperature

patterns being constant. The RAPS aircraft measurements are already being processed and analyzed as part of another grant.

Indirect Sensing of the Urban Heat Island by Satellite and the Measurement of Substrate Parameters Responsible for its Formation

T. N. Carlson, J. A. Augustine
Department of Meteorology
The Pennsylvania State University
University Park, Pennsylvania 16802

F. E. Boland
Geophysical Fluid Dynamics Laboratory, NOAA
Princeton, New Jersey 08540

ABSTRACT

Satellite-derived temperature analyses are presented for a day-night sequence over Los Angeles during October 1976. Relatively warm temperatures appear over the downtown area, industrial sections, and medium rise high density suburbs; cooler temperatures are observed over the less populated suburbs and over wooded terrain. Such thermal contrast is clearly related to the surface layer heating and reflects the nature of land use and the character of the ground surface. We outline a method whereby a numerical surface layer temperature/heat flux model may be used to obtain by inversion, quantitative estimates of the thermal inertia and moisture availability which are essentially responsible for the formation of the urban heating pattern.

SATELLITE OBSERVATIONS

One of the more obvious manifestations of urbanization is the heat island which is represented by relatively warmer temperatures over built-up areas and cooler temperatures in the suburbs. This phenomenon has been studied for over a hundred years, but it has only been recently that systematic attempts have been made to mathematically model the causes of its formation. Likewise, remote sensing of the urban heat island has only become possible with the launching of GOES, NOAA, ERTS, and the proposed HCMM satellites which carry radiometers whose spatial resolution provides the necessary detail for mapping the intricate thermal patterns over the diverse urban canopy. The polar-orbiting sun synchronous NOAA satellites, for example, are capable of making two passes a day over most locations; they contain, among other things, VHRR radiometers which operate in both the visible (0.6 - 0.7 μm) and infrared (10.5 - 12.5 μm) with a resolution of just under 1.0 km at zero nadir angle and about 1.5 km at the edge of the scan.

We have applied NOAA-3 and 5 satellite measurements in an investigation of heating patterns over the greater Los Angeles area using both the visible reflectances and the equivalent black body temperature measurements which are derived from the infrared radiances - (1)*. An example of a day-night pair of satellite temperature maps for Los Angeles, corrected for water vapor absorption - (2) and redrawn from the machine-analyzed output, is shown in Figs. 1 and 2. Three hours after sunrise (Fig. 1) a pronounced warm maxima ($T \sim 29°C$) is observed over an industrial zone (N) not far from the centeral business district (B) and the high density residential suburbs (H). Relatively high temperatures are also found over a region of oil fields (O). Other oil fields, the airports and military installation (M), though sparcely populated, are associated with locally warmer temperatures ($T \sim 28°C$). Higher and more wooded locations, portions of the Palos-Verdes Peninsula (P) and the Santa Monica Mountains (S), appear noticably cooler.

In the evening (Fig. 2) warm temperatures remain over the inner city ($T \sim 18°C$) but the maximum has shifted somewhat toward the central business district and the high density suburbs. The oil fields and airports ($T \sim 15$-$16°C$) cooled more rapidly than the central business district while less rapid cooling occurred over parts of the Santa Monica Mountains. One curious feature of these mountains is the presence of very warm temperatures ($T \sim 19$-$20°C$) along their southern flanks, in response to the direct solar heating of these slopes by the late afternoon sun; cooler temperatures associated with the shading effect can be seen on the northern slopes. Very little temperature change occurs over the ocean.

Such temperature patterns as shown in Figs. 1 and 2 implicitly contain information concerning the surface energy budget (in particular the sensible heat flux) and, consequently, they represent an indirect but quantitative measure of land use. In principle, a surface heat budget can be verified experimentally over a stretch of homogeneous terrain whose surface characteristics are well known. On the other hand, it is not apparent how one would uniquely measure a heat flux, or a particular substrate variable over an inhomogeneous tract of land containing a mixture of surface types. Yet, in order to model correctly the urban boundary layer and ultimately to predict the air flow and the development of the urban mixed layer, it is necessary to represent the surface heat input with some degree of detail. In turn, the heating patterns are themselves strongly tied to the character of the surface and substrate even though the nature of the surface is exceedingly difficult to define or to measure directly. Strictly speaking, Figs. 1 and 2 do not depict the urban heat island itself, which is an anomaly of the air temperature pattern. Rather, these ground temperatures are a more direct reflection of the surface heat flux pattern which constitutes a driving mechanism for the urban heat island.

APPLICATION OF SURFACE-LAYER MODEL CALCULATIONS TO SATELLITE OBSERVATIONS

It is clear, however, that these satellite temperatures respond to changes in the surface character. In a mathematical model of the surface temperature, various surface or substrate properties for an ideal ground medium, (roughness, albedo, conductivity, diffusivity) strongly influence the temperature wave at the ground-air interface. Over heterogeneous terrain such as that of an urbanized region, these terrain properties constitute effective parameters which yield the correct (i.e. the observed) surface temperatures in the model. In order to verify such model results, however, an effective ground temperature must be determined.

Such an observation can be provided by satellite. Satellite derived temperature measurements are essentially instantaneous over a small region and are accurate to within an uncertainty of 1-2°C, the error arising primarily from horizontal variations in surface emissivity and atmospheric turbidity. We have developed a one-dimensional numerical boundary layer model which is capable of simulating the surface

*Numbers in parentheses designate References at the end of paper.

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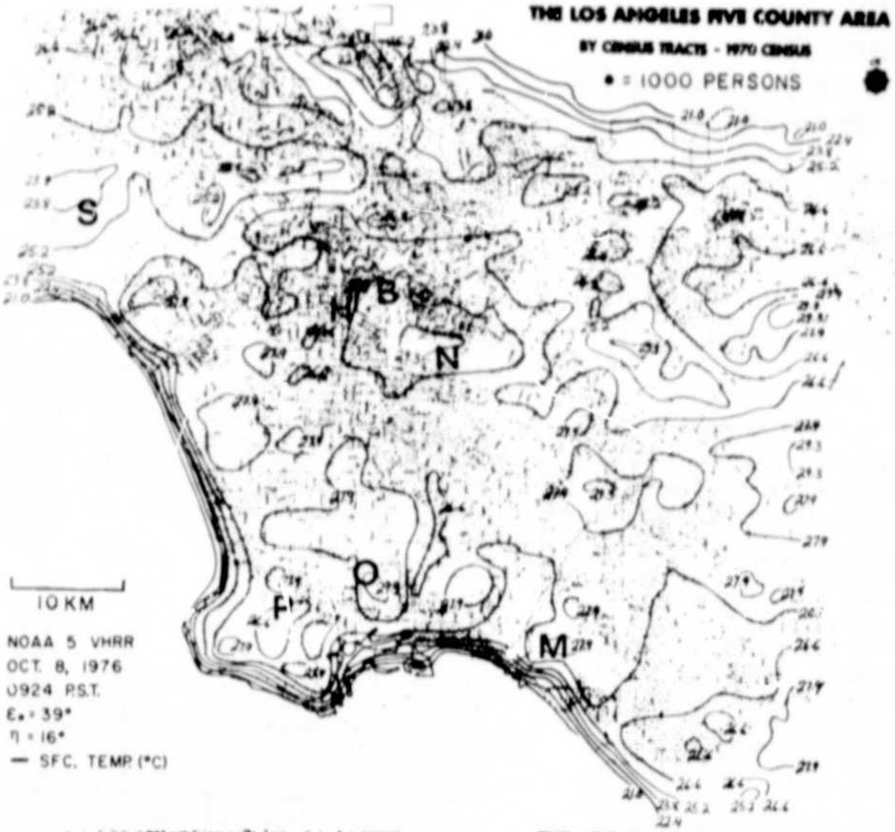

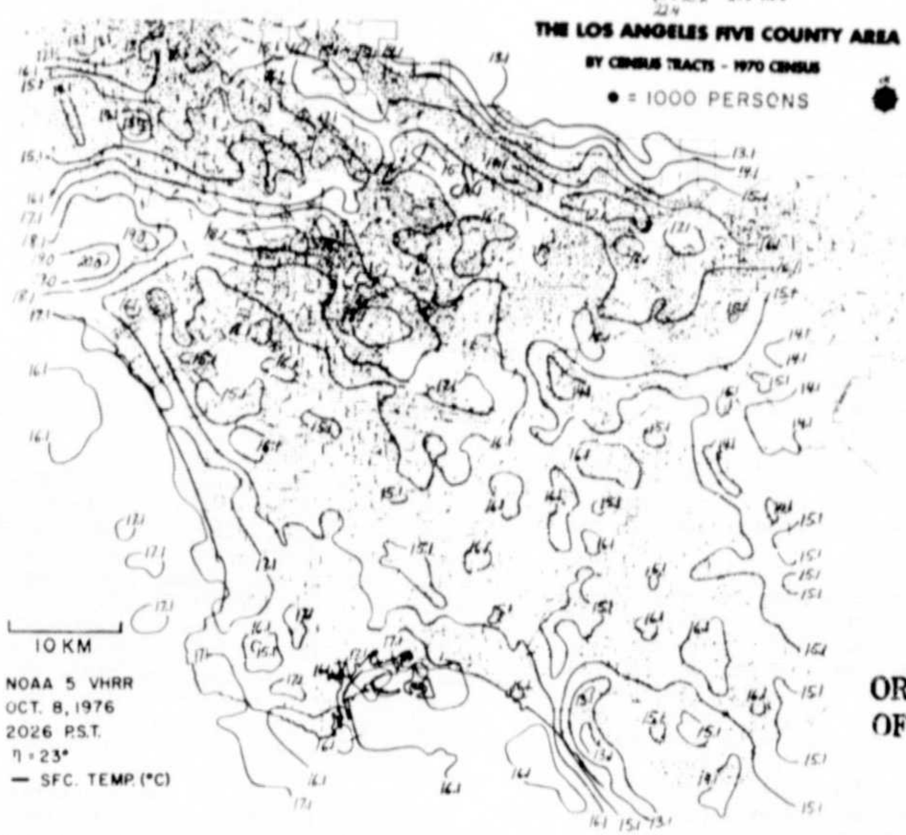

Fig. 1. - (top) Surface infrared temperature analyses derived from NOAA-5 VHRR measurements for orbit 879 at 0924 PST, 8 October, 1976. Solar and zenith angles are, respectively, 39 and 16 degrees. Letters represent geographical locations (see text).

Fig. 2. - Same as Fig. 1 but for orbit 885 at 2026 PST. Nadir angle was 23 degrees.

temperature and heat flux with an accuracy comparable to that obtainable from satellite, given the radiative forcing and values for the meteorological and surface parameters - (3,4). Similar types of models have gained a wide acceptance in the literature - (5,6,7).

Our analysis indicates that except in winter and in colder climates, two primary input parameters are responsible for the formation of significant horizontal temperature variations and thus the urban heat island. One such parameter is the thermal inertia of the substrate P (sometimes called the thermal property or conductive capacity) which is equal to $C\kappa^{1/2}$, where C is the substrate heat capacity and κ is the thermal diffusivity of the medium. The other is the moisture availability of the substrate M, which represents the efficiency of evaporation from the ground medium, i.e., the ratio of water vapor flux to that for a saturated surface. Although ground albedo, surface roughness and horizontal wind speed are important secondary determinants of the heating patterns over urban areas, the correct temperatures can be modeled for clear sky cases to within an uncertainty of ~1 to 2°C, given the low level wind speed and reasonable estimates of the secondary ground parameters. No hydrodynamic surface-layer model, however sophisticated in construction, can reproduce the surface temperature wave and thus the surface heating pattern without a fairly accurate specification of the two dominant substrate parameters, M and P. In order to model the horizontal temperature pattern with a relative uncertainty of no greater than 1-2°C, both P and M must be accurate to within about 10 to 20% of their natural horizontal variability across the urban-rural complex. This amount is too small a variation to be determined by a simple guess. Rather than measure these substrate properties directly, which is infeasible, it is more convenient to consider them as effective parameters which can be obtained from the observed surface temperatures by inversion of the model.

To illustrate the inversion procedure, consider a simulated temperature wave generated by the model over a period of time, say one day. All model parameters are fixed during this period, but the experiment is run a large number of times with different values of M and P, and the temperatures printed out at a particular time, t_a. Accordingly, a matrix of temperature values T_{ka} is produced as in Fig. 3, which contains a family of isotherms ($T_k=T_1,T_2,T_3 \ldots$), each one corresponding to an infinite set of M, P pairs. One isotherm represents the observed temperature T_{ka} at the time t_a during the heating cycle. If, deriving the same set of numerical experiments, the temperatures are generated at two times during the heating cycle (with the same set of input constants), a second family of temperature lines are produced which can be superimposed on a common matrix with the first set of lines. Now the pair of observed temperatures T_{ka} and T_{kb} at times t_a and t_b, in corresponding to two isotherms in the M-P space of Fig. 3, are likely to intersect at a point which uniquely determines a pair of M and P values satisfying conditions for the observed pair of temperatures. If the model is properly constituted and the secondary terrain parameters and meteorological variables specified realistically, the solutions should occur within the matrix rather than at an unacceptable location outside the grid, for example at negative M.

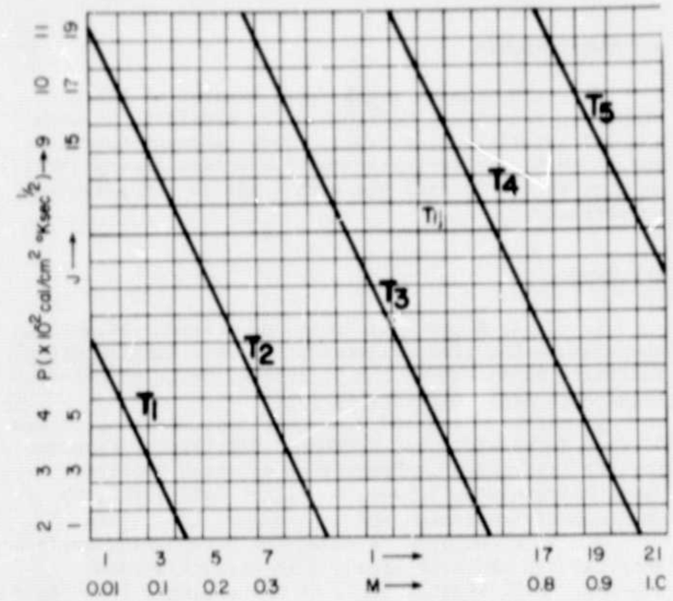

Fig. 3. - Schematic array of temperatures T_{ka} derived from model results for pairs of M and P values.

Solutions leading to recovery of these substrate parameters can be obtained by such graphical methods or by numerical-iterative machine computations. Using the latter method we find that solutions rapidly converge to precise values of M and P and that the recovered substrate parameters when substituted back into the model yield temperatures very close to the starting ones. Greatest accuracy will be attained, however, when the temperatures are changing slowly with time and have widely differing values at t_a and t_b such as at noon and midnight. Given the recovered substrate parameters, the entire surface energy balance can be determined.

Our examination of satellite-derived surface temperature maps of Los Angeles reveals that the overall configuration of the temperature patterns (illustrated in Figs. 1 and 2) persists throughout the year, indicating that the configuration of substrate properties is relatively stable and not greatly affected by meteorological changes - (1). Because of the intimate association between temperature and heat flux, recovery of the substrate parameters would enable one to determine the surface energy budget on days when no direct temperature observations are available, an obvious benefit for application in hydrodynamic models of the atmosphere. The inversion method has yet to be tested with real satellite temperature measurements because the NOAA satellite orbits occur at transitory stages in the heating cycle, not long after sunrise and sunset. More useful observations are those which would be obtained close to the times of maximum and minimum temperature. The method of combining observation with model inversion is, of course, general and leads itself readily to the study not only of urban heating patterns but of soil moisture for agricultural and other purposes.

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